

Airborne 2-micron double-pulsed integrated path differential absorption lidar for column CO₂ measurement

Upendra N. Singh^a, Jirong Yu^a, Mulugeta Petros^a, Tamer F. Refaat^b, Ruben G. Remus^a, James J. Fay^a and Karl Reithmaier^c

^aNASA Langley Research Center, 11 Langley Blvd., Hampton, VA USA 23681; ^bApplied Research Center, 12050 Jefferson Ave., Newport News, VA USA 23606; ^cScience System & Applications, Inc., 1 Enterprise Parkway, Hampton, VA USA 23666

ABSTRACT

Double-pulse 2-micron lasers have been demonstrated with energy as high as 600 mJ and up to 10 Hz repetition rate. The two laser pulses are separated by 200 μ s and can be tuned and locked separately. Applying double-pulse laser in DIAL system enhances the CO₂ measurement capability by increasing the overlap of the sampled volume between the on-line and off-line. To avoid detection complicity, integrated path differential absorption (IPDA) lidar provides higher signal-to-noise ratio measurement compared to conventional range-resolved DIAL. Rather than weak atmospheric scattering returns, IPDA rely on the much stronger hard target returns that is best suited for airborne platforms. In addition, the IPDA technique measures the total integrated column content from the instrument to the hard target but with weighting that can be tuned by the transmitter. Therefore, the transmitter could be tuned to weight the column measurement to the surface for optimum CO₂ interaction studies or up to the free troposphere for optimum transport studies. Currently, NASA LaRC is developing and integrating a double-Pulsed 2- μ m direct detection IPDA lidar for CO₂ column measurement from an airborne platform. The presentation will describe the development of the 2- μ m IPDA lidar system and present the airborne measurement of column CO₂ and will compare to in-situ measurement for various ground target of different reflectivity.

Keywords: Double-pulsed laser, IPDA lidar, Integrated-path differential absorption lidar, Carbon dioxide, DIAL

1. INTRODUCTION

Carbon dioxide (CO₂) is an important greenhouse gas that significantly contributes to the carbon cycle and global radiation budget on Earth. CO₂ role on Earth's climate is complicated due to different interactions with various climate components that include the atmosphere, the biosphere and the hydrosphere [1-2]. These interactions define the gas sources and sinks that affect the worldwide CO₂ transport fluxes. Understanding the interactions and transport of atmospheric CO₂ around Earth is critical for carbon cycle studies and climate predictions through environment models [3-5]. Although extensive worldwide efforts for monitoring atmospheric CO₂ through various techniques, including *in-situ* and passive sensors, are taking place high uncertainties exist in quantifying CO₂ sources and sinks. These uncertainties are mainly due to insufficient spacial and temporal mapping of the gas. Therefore it is required to have more rapid and accurate CO₂ monitoring with higher uniform coverage and higher resolution. This was addressed by many international satellite missions. Although CO₂ satellite missions are based on passive-sensors, they offered many advantages over *in-situ* measurements including the ability of continuously measuring the gas in tropical regions and over southern oceans [1-2]. Present satellite instruments monitoring CO₂ from space include SCIAMACHY, TES, AIRS, IASI, GOSAT and OCO-2 [6-11]. Among these, OCO-2 is fully dedicated for CO₂ monitoring and focusing mainly on the gas sources and sinks [11]. Some of these satellite systems have shown the potential to meet the spatial coverage to improve CO₂ flux estimates on continental scales. However, satellite passive remote sensors are unable to meet the accuracy required to aid in better quantifying the terrestrial sources and sinks due to some limitations. For instance, shortwave infrared instruments rely on solar illumination which restricts their orbits and latitudinal coverage. Alternatively, thermal infrared systems relying on Earth's radiation are not sensitive to the lower atmosphere where the largest CO₂ interactions occur. Furthermore, passive remote sensing systems involve retrieval complexities which suffer from aerosol and cloud contamination and radiation path length uncertainties [12]. Active remote sensing of CO₂ is an alternative technique that has the potential to overcome the limitation of the passive sensors.

CO₂ active remote sensing has been demonstrated using the differential absorption lidar (DIAL) technique [13-21]. Both 1.6 and 2.0 μm are suitable for atmospheric CO₂ measurements due to the existence of distinct absorption features for the gas at these particular wavelengths. Although CO₂ DIAL systems demonstrations were provided for systems validity from ground or airborne platforms, a complete CO₂ DIAL mission that contributes to the science community has not been established yet. A number of worldwide teams have been engaged in developing CO₂ DIAL instruments using different transmitters and detection methods. In France, a CO₂ DIAL was developed based on 2- μm pulsed crystal-open path cavity transmitter and heterodyne detection [13]. In Germany a 1.6- μm pulsed optical parametric oscillator transmitter with direct detection has been developed [14]. In Japan similar systems were developed for ground based measurement [15-16]. In the USA, the National Research Council Decadal Survey recommended an active laser-based CO₂ mission, “Active Sensing of CO₂ Emissions over Night, Days, and Seasons (ASCENDS)”, to increase our understanding of CO₂ sources, sinks, and fluxes worldwide [1]. Research groups at NASA are currently involved in developing different CO₂ DIAL instruments. Two of these instruments operate at 1.6 μm have been developed and deployed as airborne systems for atmospheric CO₂ column measurements [17, 19]. One instrument is based on an intensity modulated continue wave (CW) approach [19], the other on a high pulse repletion frequency, low pulse-energy approach [17]. These airborne CO₂ DIAL systems operating at 1.57- μm utilize mature laser and detector technologies by taking advantage of the technology development outcomes in the telecom industry.

CO₂ DIAL operating in the 2- μm band offer better near-surface CO₂ measurement sensitivity due to the intrinsically stronger absorption lines. Using a 2.05- μm CW laser absorption spectrometer employing coherent detection method, airborne measurements of CO₂ column abundance has been demonstrated [18]. For more than 15 years, NASA Langley Research Center (LaRC) contributed in developing several 2- μm CO₂ DIAL systems and technologies. This paper focuses on the current development of the airborne double-pulsed 2- μm CO₂ integrated path differential absorption (IPDA) lidar system at NASA LaRC. This includes the IPDA system development and integration. Results from ground and airborne CO₂ IPDA testing will be presented. The potential of scaling such technology to a space mission will be addressed.

2. TWO-MICRON CARBON DIOXIDE IPDA LIADR SYSTEM

Double-pulse 2- μm lasers have been developed with energy as high as 600 mJ and up to 10 Hz repetition rate [22]. A single pump pulse produces the two laser pulses at the 2- μm wavelength which are separated by 150 to 200 μs . Using a unique wavelength controller, both pulses can be tuned and locked separately around 2.05 μm wavelength. Implementing this laser in a CO₂ IPDA system, the first and second pulses are tuned and locked to strong and weak absorption features of the molecule known as the on-line and off-line wavelengths, respectively. Applying the double-pulse laser in IPDA system enhances the CO₂ measurement capability by increasing the overlap of the sampled volume between the on-line and off-line [23-24]. IPDA offers measurements with higher signal-to-noise ratio compared to conventional range-resolved DIAL. This is due to the fact that IPDA rely on the much stronger energy monitor and hard target return signals that are best suited for airborne platforms, rather than weak atmospheric scattering return signals which are provided in range-resolved DIAL. In absence of range profiling, the IPDA technique measures the total integrated column content from the instrument to the hard target but with weighting that can be tuned by controlling the transmitted wavelengths. Therefore, the transmitter could be tuned to weight the column measurement to the surface for optimum CO₂ interaction studies or up to the free troposphere for optimum transport studies. This is achieved, for example, by tuning the on-line wavelength to different positions relative to the R30 CO₂ line as shown in figure 1. Currently, NASA LaRC is developing and enhancing IPDA data processing algorithms for CO₂ column measurement from an airborne platform [23-24]. Figure 2 shows an isometric view and a picture of the key components of the 2- μm CO₂ IPDA system.

2.1 IPDA Lidar Transmitter

The compact, rugged, highly reliable CO₂ IPDA laser transmitter is capable of generating above than 100 mJ total energy at 10 Hz repetition rate [22-23]. This transmitter is based on the Ho:Tm:YLF high-energy 2- μm pulsed laser technology. This laser transmitter is side pumped by AlGaAs diode arrays at 792 nm and designed to operate in a unique double pulse format to mitigate the effect of the surface reflection difference between the on-and-off line pulses on the precision of the IPDA measurement. When the Ho upper laser level population reaches its maximum value at the end of the pump cycle, a first Q-switched pulse is generated which extracts the energy stored in the Ho ⁵I₇ upper level, resulting in a sharp decrease in the upper level population. Then, a new population equilibrium between the Tm ³F₄ and the Ho ⁵I₇

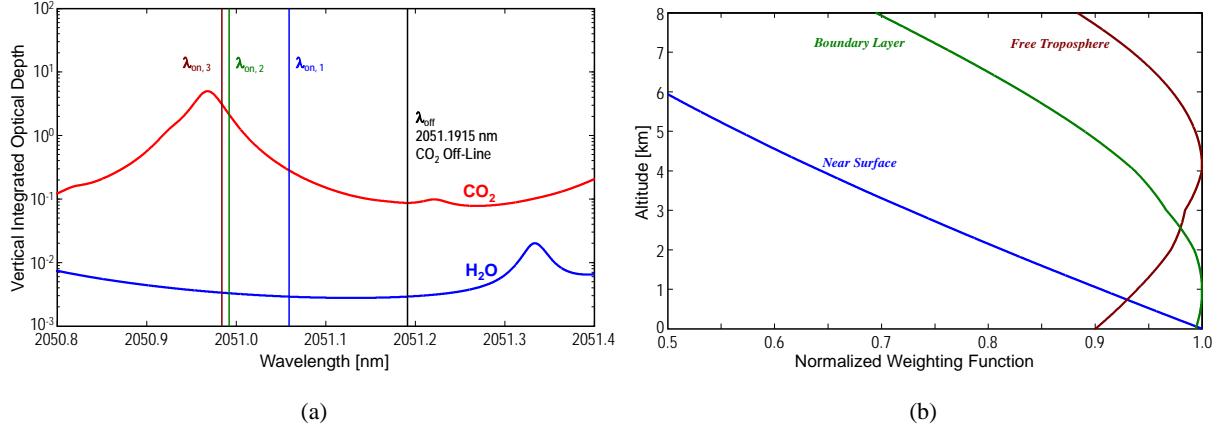


Figure 1. (a) CO₂ integrated optical depths calculation derived using the HITRAN 2008 data base for line parameters and US Standard model for metrological profiles compared to the higher abundant water vapor (H₂O) interfering molecule. Vertical lines mark examples of selected on-line wavelengths and off-line wavelength that would result in different CO₂ sensing weighting-function. Thus weighting-function peak can be tuned to the surface, top of the boundary layer or the free troposphere as shown in (b).

manifolds is established by energy transfer from the excited Tm ions towards Ho ions even though the pump no longer exists. Then the population at Ho upper laser level ⁵I₇ comes to its second maximum about 150 μs after the first pulse. At this instance a second Q-switch pulse is triggered resulting in a second laser pulse. Therefore, the desired double pulse operation is achieved using a single-pump. This is a unique feature of this laser transmitter that it provides two Q-switched pulses with a single pump pulse [22].

The exact wavelengths of the pulsed laser transmitter are controlled by a wavelength control unit. The first pulse and the second pulse are injection seeded alternatively by the on-line and the off-line wavelengths, respectively. All the optical mounts are custom designed with space heritage. They are designed to be adjustable and lockable and hardened to withstand vibrations that can occur during operation in an airborne environment. Figure 3a shows a picture of the engineering packaged laser transmitter. This laser transmitter is 11.5 \times 26.5 \times 6.4 inch (29 \times 67.3 \times 16.5 cm) in size, and weighted less than 70lbs (31.75 kg). Transmitter packaging includes a beam expander at the laser outlet which results in a final 2.54 cm output beam diameter.

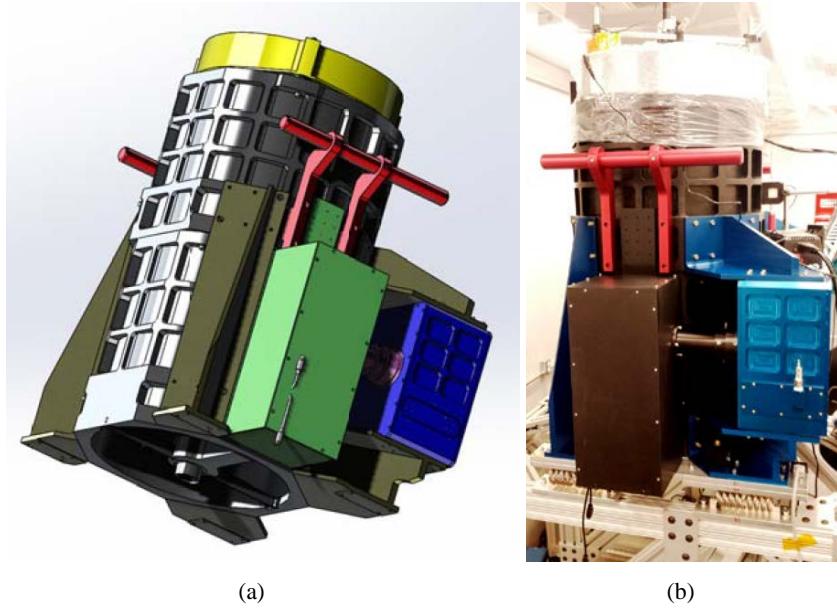


Figure 2. (a) Isometric view and (b) a picture of the key components of the 2- μm CO₂ IPDA lidar system. These includes the telescope structure (gray), primary mirror (yellow), laser transmitter box (blue) and beam steering optics (green).

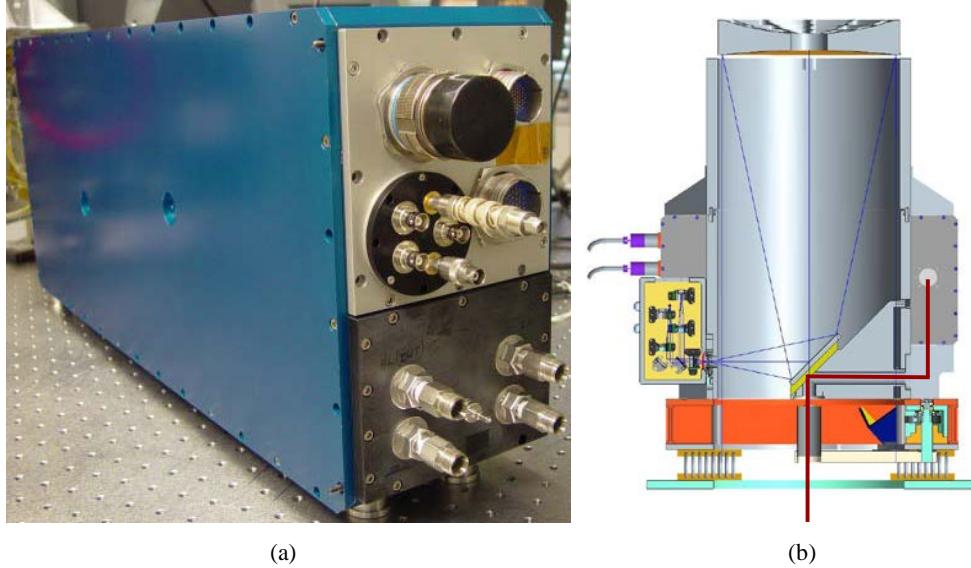


Figure 3. (a) Package 2- μ m IPDA laser transmitter. The transmitter is 11.5×26.5×6.4 inch (29×67.3×16.5 cm) in size, and weighted less than 70lbs (31.75 kg). (b) Schematic of the 2- μ m IPDA receiver system. Red lines mark the expended transmitted beam and blue lines mark the return radiation focused onto the detectors.

2.2 IPDA Lidar Receiver

The IPDA receiver consists of a telescope that focuses the radiation onto two detectors through aft-optics. The receiver telescope is a custom designed Newtonian type with 40cm diameter aluminium primary mirror. The shape of the primary mirror is hyperbolic to minimize the aberration, so that the returning signal can be focused to less than 300 μ m diameter spot size compatible with the radiation detectors. The telescope is designed to maintain the focus point position in the temperature range between 5 and 35 °C. 300 μ m diameter InGaAs pin photodiodes (Hamamatsu; G5853) were selected for this mission. Two detectors accommodate high and low gain optical channels after beam splitting. Detector characterization resulted in a noise-equivalent-power of 6.8×10^{-14} W/Hz^{0.5} at 30°C that is suited for the 2- μ m IPDA lidar application. After amplification, the lidar signals are digitized and stored through a data acquisition unit. The data acquisition unit is based on two digitizers. The first is a 10-Bit, 2 GS/s digitizer (Agilent; U1065A) for laser energy monitoring and the second is a 12-bit, 420 MS/s digitizer (Agilent; U1066A) for measuring the hard target returns. Detectors are coupled to the digitizers through variable gain, high speed trans-impedance amplifiers (FEMTO; DHPGA-100). Digitizers and data storage are hosted through a personal computer that runs Microsoft XP with a 64-bit/66 MHz PCI bus. The system is capable of transferring data at sustained rates up to 400 MB/s to the host computer. Figure 3b shows a schematic of the IPDA receiver including ray tracing of the transmitted and collected radiation [23-24].

3. IPDA LIDAR GROUND TESTING

The integrated IPDA lidar was installed inside a mobile trailer, shown in figure 4a, for initial testing and alignment verification. A 24 inch flat mirror was installed underneath the telescope at 45° for turning the transmitted beam and telescope field-of-view from nadir to horizontal direction through a side window, as shown in figure 4b. This allows pointing the IPDA to a set of calibrated hard targets, with known reflectivity, located at about 857 m away from the trailer. Figure 5a shows an aerial picture of the test site at NASA LaRC. Collocated in the site is the Chemistry and Physics Atmospheric Boundary Layer Experiment (CAPABLE). CAPABLE is a ground-based observation site for studying atmospheric conditions in the Tidewater region of Virginia, which operates through collaborative effort between the Science Directorate at NASA LaRC, the U.S. Environmental Protection Agency and the Virginia Department of Environmental Quality [25]. CAPABLE instruments continuously measure pollutants, such as ozone, nitrogen dioxide, carbon monoxide and aerosols. Beside, CAPABLE provides continuous ground meteorological



(a)

(b)

Figure 4. (a) 35 ft trailer used as a mobile laboratory for hosting the 2- μm CO₂ IPDA lidar for ground testing. A 17 inch widow on the trailer side provides IPDA access to calibrated hard targets. (b) IPDA inside the trailer installed on an aluminium frame. A 45° 24 inch mirror directs the IPDA to the calibrated hard targets.

monitoring, such as pressure, temperature and relative humidity. This data is valuable for the 2- μm CO₂ IPDA lidar modelling for instrument validation on ground. In addition, an *in-situ* CO₂ and H₂O gas analyser (LiCor; LI-840A) was installed at fixed location as shown in figure 5a. This allows better estimates of the CO₂ mixing ratio in the test location for better evaluation of the 2- μm CO₂ IPDA lidar instrument. Finally, it is worth mentioning the collocation of the Hampton-NASA Steam Plant [26], which is a solid waste incinerator (figure 5a) used for steam generation. Depending on the incinerator operating cycles, higher than normal CO₂ mixing ratio was observed at the IPDA test location.

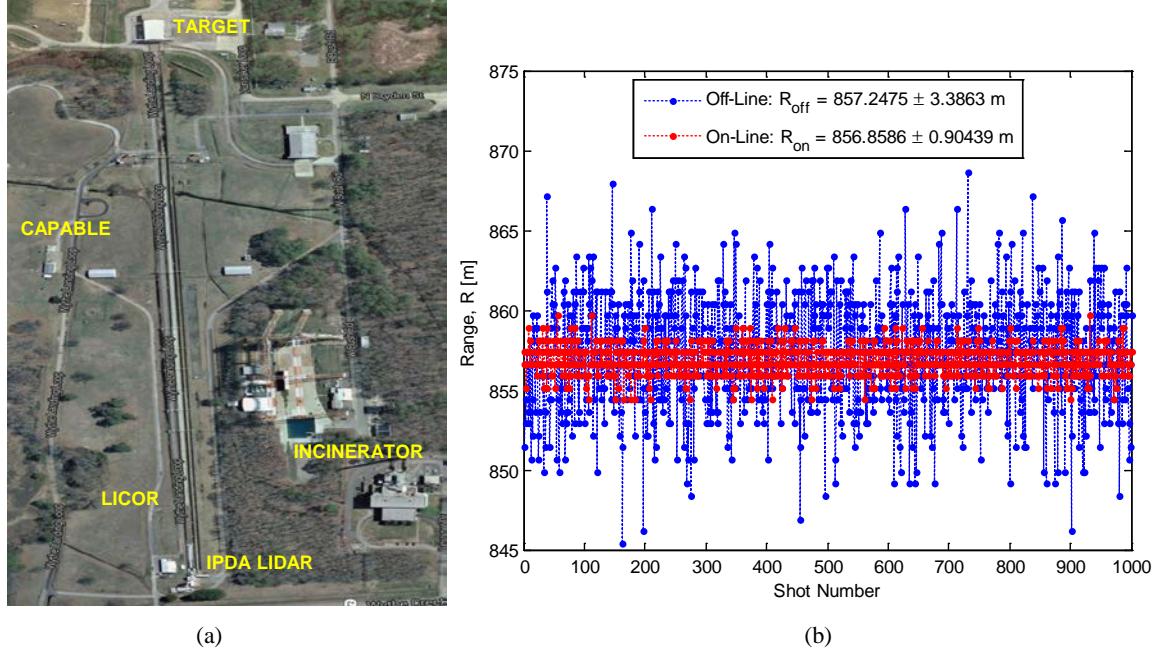


Figure 5. (a) Aerial picture of the 2- μm CO₂ IPDA ground testing site at NASA LaRC. (b) IPDA range determination using both the 2 GHz on-line and off-line wavelengths.

IPDA lidar ground testing included different operating conditions, in terms of signal conditioning settings, target reflectivity and on-line offsets from the CO₂ R30 line center. Ranging capability is another advantage of the pulsed IPDA lidar. Range measurement between the IPDA and the hard target was achieved by monitoring the time delay between the transmitted and return pulses. Converting the time delay into distance using the speed of light the IPDA column length is determined, as demonstrated in figure 5b, for both on-line and off-line wavelengths. Results are consistent with the nominal setting of the trailer relative to the hard target. Preliminary analysis of the ground test data indicated IPDA lidar sensitivity to atmospheric CO₂ concentration. Figure 6a compares the CO₂ differential optical depth measured by the IPDA lidar to the theoretical value. After cleaning the IPDA data, differential optical depth was obtained by calculating the natural logarithm of the off-line to the on-line return energy after normalization to the transmitted laser energy (laser energy monitor). The theoretical differential optical depth was derived using the US standard atmospheric model [27]. The IPDA data cleaning process involves eliminating saturated, clipped and missing shots from the data stream. This results in rejecting about 10% of the data record, which are replaced by linear interpolation. Besides, the IPDA measured differential optical depth was converted to CO₂ dry mixing ratio, using metrological data obtained from CAPABLE. Figure 6b compares the CO₂ dry mixing ratio calculated using the IPDA results to the measured using the *in-situ* sensor. General temporal profile agreement is observed between both curves, after correcting for 50 ppm offset which is caused due to nonlinearities. Higher than normal CO₂ dry mixing ratio is observed caused probably due to incinerator operation.

4. IPDA LIDAR AIRBORNE TESTING

The 2- μ m CO₂ IPDA lidar is designed for integration into a small research aircraft. The IPDA instrument size, weight and power consumption were restricted to the NASA B-200 payload requirements. This allows the system to be easily adopted in any larger airborne research platform, such as the NASA DC-8 aircraft, for future missions. In addition to the IPDA lidar, other housekeeping instruments were integrated into the B-200 aircraft. These included the *in-situ* sensor (LiCor) for CO₂ dry mixing ratio measurement, GPS for aircraft position, altitude and angles measurements and video recorder for target identification. Besides, aircraft built-in sensors provided altitude, pressure, temperature and relative humidity sampling at the flight position. Time stamps were adjusted to the GPS global timing. Figure 7 shows the NASA B-200 aircraft and the integrated IPDA instrument inside. Two operators are required to accompany the instrument during operation.

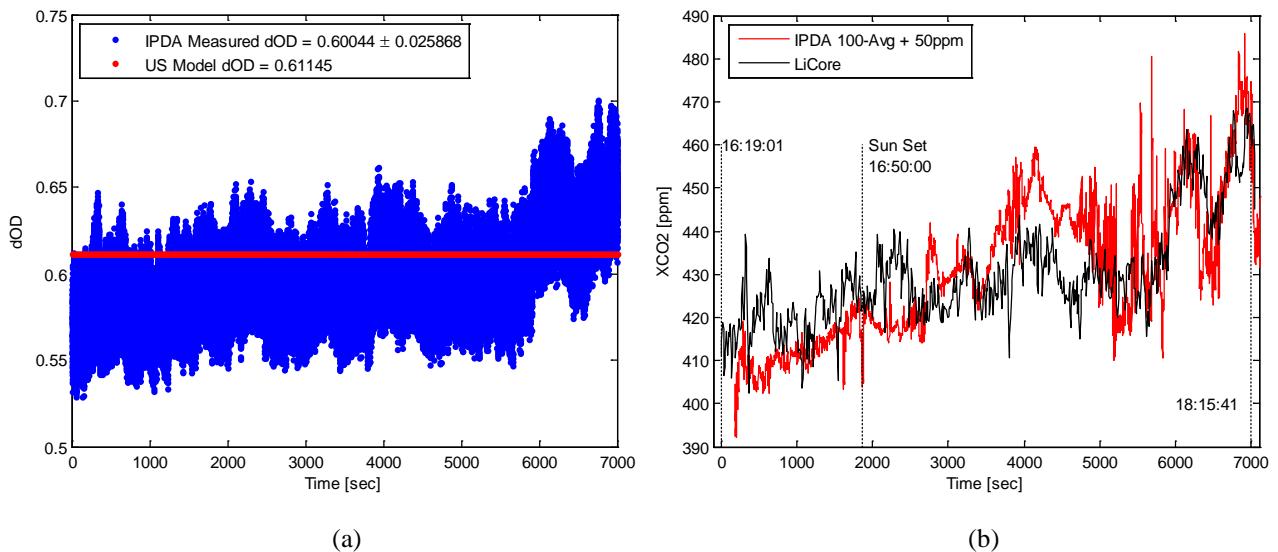


Figure 6. (a) Single-shot CO₂ double-path differential optical depth measurement obtained from the IPDA lidar compared to theoretical value calculated using US standard model. (b) 2 μ m IPDA integrated-column CO₂ dry mixing ratio comparison with *in-situ* measurement. IPDA CO₂ dry mixing ratio was obtained using CAPABLE data for differential optical depth conversion after 10 sec averaging. Data collected using 2 GHz on-line offset.



(a)

(b)

(c)

Figure 7. (a) Some team members participated in the 2- μm CO₂ IPDA lidar airborne testing in front of the NASA B-200 aircraft. 2- μm IPDA lidar instrument (a) and electronic rack (b) integrated inside the aircraft.

The 2- μm CO₂ IPDA lidar airborne testing was conducted during ten daytime flights, spanning more than 27 hours, during March 20, 2014 through April 10, 2014. Meteorological balloon radiosonde was independently launched from CAPABLE site, mostly during the beginning and the end of each flight. This allows for atmospheric pressure, temperature and relative humidity vertical profiling estimates for IPDA modelling verifications. IPDA lidar airborne testing included different operating and environmental conditions. Environmental conditions included different flight altitude up to 6 km, different ground target conditions such as vegetation, soil, ocean, snow and sand and different cloud conditions. Besides, some flights targeted power plant incinerators for investigating the IPDA sensitivity to CO₂ plumes. Table 1 lists these flight and summarizes the conditions. Flights were conducted from NASA LaRC through Langley Air force Base, Hampton, Virginia. In the first three flights (engineering flights 1, 2 & 3), the objective was to check the IPDA instrument operation and alignment verification in the airborne environment at different altitudes ranging from 3kft to 27.5kft. Ground condition was maintained almost fixed by targeting soil/vegetation through a flight track to the west of Virginia from Franklin to South Boston. The objectives of the fourth and fifth flights were to test different ground target condition in terms of different reflectivity versus signal return power at a fixed altitude of 22kft. Taking advantage of an early spring snow storm, flight 4 headed north toward Northern Virginia were soil, vegetation and snow were the investigated targets. On the same day, flight 5 headed south toward the Outer Bank of North Carolina to investigate soil, vegetation, sand and water targets. Focusing on the ocean surface return, the sixth flight headed toward the Atlantic where measurement conducted in clear and cloudy conditions. This took the advantage of 4kft altitude cloud coverage over the ocean, where the IPDA instrument was capable to distinguish ocean surface and cloud return with cloud depth measurement. The objectives of flights 7 and 9 were to fly over large power plant, Roxboro Power Station of North Carolina, where the high consumption of coal tends to bias the CO₂ mixing ratio above normal sources. Finally the tenth flight was objected to debugging the CO₂ in-situ sensor, over the Franklin to South Boston trajectory. Figure 8 shows the track of some of the 2- μm CO₂ IPDA lidar flights. Preliminary analysis of the airborne test data indicated the IPDA lidar sensitivity to atmospheric CO₂ up to 6 km altitude over ocean target. In spite of the mechanical stresses due to shaking and vibration in the small aircraft environment, the IPDA lidar did not losses alignment resulting in about 190 GB worth of raw data.

On April 5, 2014, the NASA B-200 eight flight coincided with another NOAA air sampling flight [28]. Due to flight control restrictions, there was a 30 minute time lag between NOAA and NASA flights. Nevertheless, the IPDA lidar on board NASA flight sampled the same geographical location as the NOAA flask samples over the Atlantic Ocean out of the east shore of New Jersey. CO₂ flask-sampling results and meteorological data provided by NOAA were valuable for the NASA LaRC IPDA lidar instrument testing. Figure 9 shows the averaged IPDA return on-line and off-line signals at different altitudes. In each record, the first pulse is attributed to systematic effects from aircraft window and/or telescope secondary mirror radiation leaks. Similar to ground testing, the altitude information can be deducted by comparing the time delay between the first pulse and the ground return pulse. Figure 10a compares the flight altitude, obtained from the GPS to the range calculated from the IPDA data. The GPS flight altitude was converted to line-of-sight measurement after correcting for the aircraft pitch and roll angles, obtained from the GPS. Figure 10b compares the CO₂ differential optical depth obtained from the IPDA data and modelled from NOAA flask sampling data. IPDA indicated a consistent CO₂ differential optical depth offset of about 0.07, similar to what was observed on ground testing.

Table 1. Summary of the 2- μm CO₂ IPDA lidar flights during March 20, 2014 to April 10, 2014 airborne testing on board the NASA B200 (529) research aircraft.

| Flight # | Author's # Operators | Date | Time | | Duration (hrs) | Location | Objective |
|----------|----------------------|-----------|---------|----------|----------------|----------|---------------|
| | | | Start | End | | | |
| 1 | 3, 5 | 3/20/2014 | 1:50 pm | 3:42 pm | 2.1 | VA | Engineering |
| 2 | 2, 3 | 3/21/2014 | 2:17 pm | 5:00 pm | 2.7 | VA | Engineering |
| 3 | 3, 4 | 3/24/2014 | 8:50 am | 11:50 am | 3.0 | VA | Engineering |
| 4 | 2, 5 | 3/27/2014 | 7:15 am | 10:15 am | 3.0 | VA | Surface |
| 5 | 3, 4 | 3/27/2014 | 1:35 pm | 4:00 pm | 2.5 | VA, NC | Surface |
| 6 | 2, 4 | 3/31/2014 | 1:30 pm | 4:00 pm | 2.5 | VA, NC | Ocean/Clouds |
| 7 | 2, 3 | 4/02/2014 | 9:24 am | 11:47 am | 2.4 | NC | Power Station |
| 8 | 2, 4 | 4/05/2014 | 1:10 pm | 4:52 pm | 3.7 | NJ | NOAA |
| 9 | 2, 4 | 4/06/2014 | 2:10 pm | 5:10 pm | 3.0 | NC | Power Station |
| 10 | 2, 5 | 4/10/2014 | 3:40 pm | 5:58 pm | 2.3 | VA | In-Situ |

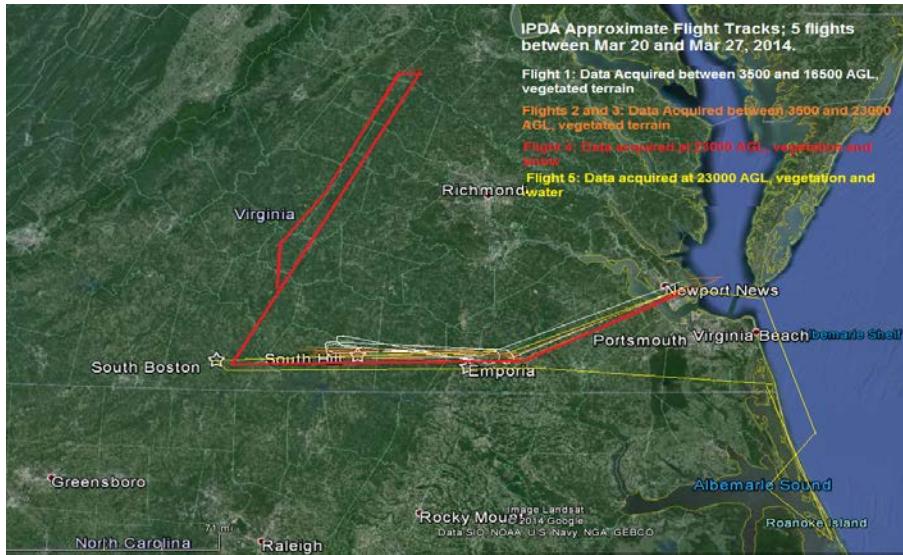


Figure 8. Flight track of some of the 2- μm CO₂ IPDA lidar test flights.

5. SUMMARY AND CONCLUSION

Understanding atmospheric CO₂ interactions and transport dynamics is important for studying carbon cycle and global radiation budget on Earth. *In-suit* and satellite based passive remote sensors have several limitations that could be recovered with active remote sensors. CO₂ active remote sensing has been demonstrated at NASA LaRC using the DIAL technique. NASA LaRC developed a double-pulse, 2- μm integrated path differential absorption (IPDA) lidar instrument for atmospheric CO₂ measurement. Advantages of the IPDA remote sensing technique include high signal-to-noise ratio measurement with accurate ranging. The 2- μm CO₂ IPDA transmitter is capable of producing 100mJ energy per pulse at 10 Hz repetition rate. High accuracy, stable and repeatable wavelength control and switching unit have been integrated within the transmitter. The IPDA also include a high quality 16 inch telescope and a commercial detector, electronics and data acquisition that has been integrated. The whole IPDA lidar structure is compactly and ruggedly packaged to fit in the NASA B-200 research aircraft. Ground and airborne testing of the 2- μm IPDA lidar was conducted at NASA LaRC through several validation procedures. This included instrument performance modeling through standard atmosphere and meteorological sampling. IPDA CO₂ differential optical depth measurement results agree with ground *in-situ* measurements and with CO₂ airborne sampling conducted by NOAA. Consistent differential optical depth offset, of about 0.1, was observed in the measurement. Further detailed data processing is under work. This airborne 2- μm IPDA lidar provides a unique CO₂ measurement tool that could be scaled to future space missions.

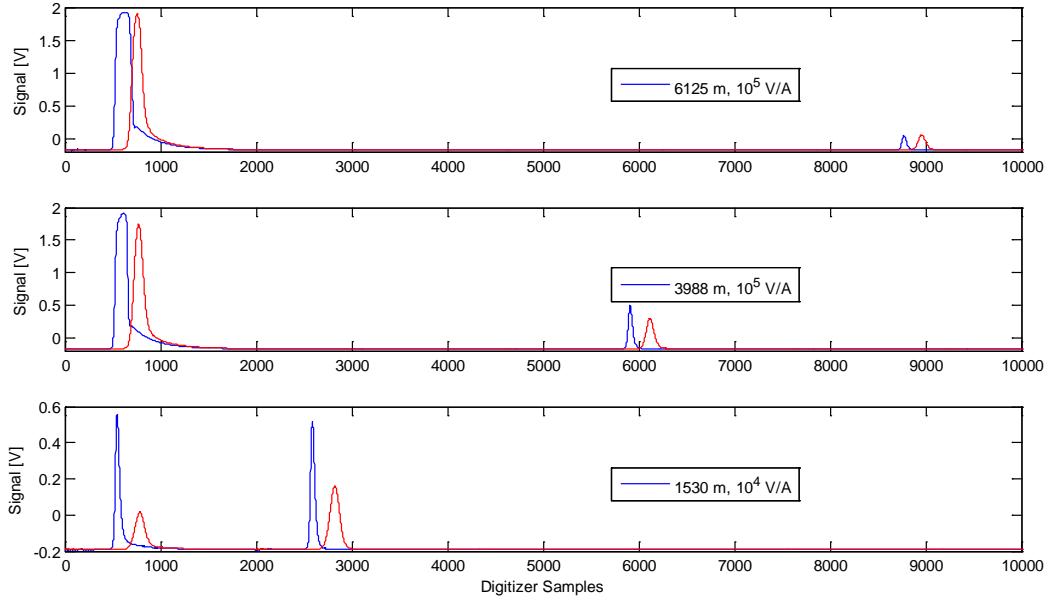


Figure 9. 2- μ m CO₂ IPDA averaged on-line and off-line return signals from different altitudes. Data collected using 4 GHz on-line offset and 200 MS/s digitizer sampling rate.

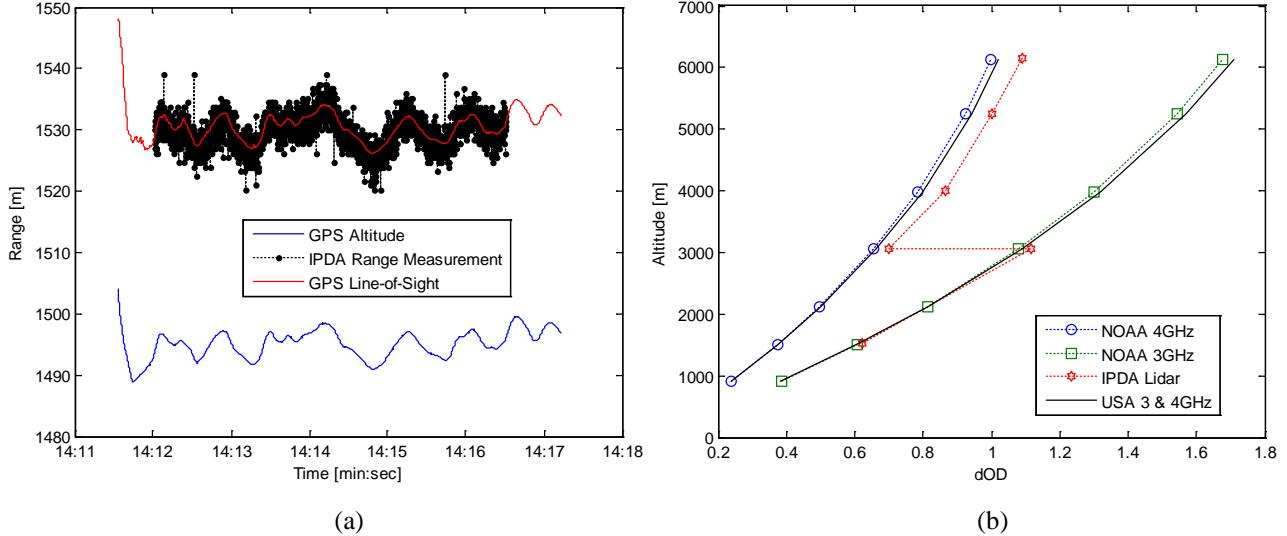


Figure 9. (a) GPS flight altitude corrected to the pitch and roll angles to obtain the IPDA line-of-sight compared to the IPDA range measurement. (b) CO₂ differential optical depth versus altitude calculated from NOAA flask sample data and from the IPDA lidar. Results are compared to US standard model calculations.

ACKNOWLEDGEMENT

The authors would like to thank NASA Earth Science Technology Office for funding this program. The authors acknowledge the support from the Engineering and Research Services Directorates at NASA Langley Research Center. Thanks are also due to the dedicated efforts of the Research Systems Integration Branch that made airborne validation possible. Acknowledgements are also due to the CAPABLE team and NOAA for providing public information that is significant for the science validation process.

REFERENCES

- [1] National Research Council, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", The National Academies Press, Washington DC, 2007.
- [2] P. Ingmann, P. Bensi, Y. Duran, A. Griva, and P. Clissold, "A-Scope – advanced space carbon and climate observation of planet earth", ESA Report for Assessment, SP-1313/1, 2008.
- [3] U. Siegenthaler, T. Stocker, E. Monnin, D. Luthi, J. Schwander, B. Stauffer, D. Ratynaud, J. Barnola, H. Fischer, V. Masson-Delmotte, and J. Jouzel, "Stable carbon cycle-climate relationship during the later Pleistocene", *Science*, 310, 1313, 2005.
- [4] B. Barnola, M. Anklin, J. Porcheron, D. Raynaud, J. Schwander and B. Stauffer, "CO₂ evolution during the last millennium as recorded by Antarctic and Greenland ice", *Tellus*, 47B, 264, 1995.
- [5] C. Keeling, T. Whorf, M. Wahlen and J. van der Plicht, "Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980", *Nature*, 375, 666, 1995.
- [6] H. Bovensmann, J. Burrows, M. Buchwitz, J. Frerick, S. Noel, V. Rozanov, K. Chance and A. Goede, "SCIAMACHY: Mission objectives and measurement modes", *Journal of the Atmospheric Sciences*, 56, 127, 1999.
- [7] S. Kulawik, D. Jones, R. Nassar, F. Irion, J. Worden, K. Bowman, T. Machida, H. Matsueda, Y. Sawa, S. Biraud, M. Fischer and A. Jacobson, "Characterization of Tropospheric Emission Spectrometer (TES) CO₂ for carbon cycle science", *Atmospheric Chemistry and Physics*, 10, 5601, 2010.
- [8] F. Chevallier, R. Engelen and P. Peylin, "The contribution of AIRS data to the estimation of CO₂ sources and sinks", *Geophysical Research Letters*, 32, L23801, 2005.
- [9] C. Crevoisier, A. Chedin, H. Matsueda, T. Machida, R. Armante and N. Scott, "First year of upper tropospheric integrated content of CO₂ from IASI hyperspectral infrared observations", *Atmospheric Chemistry and Physics*, 9, 4797, 2009.
- [10] J. Tadic, M. Loewenstein, C. Frankenberg, L. Iraci, E. Yates, W. Gore and A. Kuze, "A comparison of *in-situ* aircraft measurements of carbon dioxide to GOSAT data measured over Railroad Valley playa, Nevada, USA", *Atmospheric Measurement Techniques Discussions*, 5, 5641, 2012.
- [11] D. Hammerling, A. Michalak and S. Kawa, "Mapping of CO₂ at high spatiotemporal resolution using satellite observations: Global distributions from OCO-2", *Journal of Geophysical Research*, 117, D06306, 2012.
- [12] K. Hungershoefer, F. Breon, P. Peylin, F. Chevallier, P. Rayner, A. Klonecki, S. Houweling, and J. Marshall, "Evaluation of various observing systems for the global monitoring of CO₂ surface fluxes", *Atmospheric Chemistry and Physics*, 10, 10503, 2010.
- [13] F. Gibert, P. Flamant, D. Bruneau and C. Loth, "Two-micrometer heterodyne differential absorption lidar measurements of the atmospheric CO₂ mixing ratio in the boundary layer", *Applied Optics*, 45, 4448, 2006.
- [14] A. Amediek, A. Fix, M. Wirth and G. Ehret, "Development of an OPO system at 1.57 μm for integrated path DIAL measurement of atmospheric carbon dioxide", *Applied Physics B*, 92, 295, 2008.
- [15] S. Ishii, K. Mizutani, H. Fukuoka, T. Ishikawa, H. Iwai, P. Baron, J. Mendrok, Y. Kasai, T. Aoki, A. Sato, K. Asai and T. Itabe, "Development of 2 micron coherent differential absorption lidar", 24th International Laser Radar Conference, Boulder, Colorado, 2008.
- [16] D. Sakaizawa, C. Nagasawa, M. Abo, Y. Shibata and T. Nagai, "Development of a 1.6 μm CO₂ DIAL transmitter using OPM-OPO", 24th International Laser Radar Conference, Boulder, Colorado, 2008.
- [17] J. Abshire, H. Riris, G. Allan, S. Kawa, J. Mao, E. Wilson, M. Stephen, M. Krainak, X. Sun and C. Weaver, "Laser sounder approach for global measurements of tropospheric CO₂ mixing ratio from space", 24th International Laser Radar Conference, Boulder, Colorado, 2008.
- [18] R. Menzies and G. Spiers, "Airborn laser absorption spectrometer for IPDA measurement of atmospheric effects on attainable precision and a technique for cloud and aerosol filtering", 24th International Laser Radar Conference, Boulder, Colorado, 2008.
- [19] J. Dobler, F. Harrison, E. Browell, B. Lin, D. McGregor, S. Kooi, Y. Choi and S. Ismail, "Atmospheric CO₂ column measurements with an airborne intensity-modulated continuous wave 1.57 μm fiber laser lidar", *Applied Optics*, 52, 2874, 2013.
- [20] T. Refaat, S. Ismail, G. Koch, M. Rubio, T. Mack, A. Notari, J. Collins, J. Lewis, R. De Young, Y. Choi, N. Abedin and U. Singh, "Backscatter 2-μm lidar validation for atmospheric CO₂ differential absorption lidar applications", *IEEE Transaction on Geoscience and Remote Sensing*, 49, 572, 2011.
- [21] T. Refaat, S. Ismail, G. Koch, L. Diaz, K. Davis, M. Rubio, N. Abedin and U. Singh, "Field testing of a two-micron DIAL system for profiling atmospheric carbon dioxide", 25th International Laser Radar Conference, St. Petersburg, Russia, 2010.

- [22] J. Yu, A. Braud and M. Petros, “600-mJ, double-pulse 2- μ m laser”, Optics Letters, 28, 540, 2003.
- [23] J. Yu, M. Petros, K. Reithmaier, Y. Bai, B. Trieu, T. Refaat, M. Kavaya, U. Singh, S. Ismail, “A 2-micron pulsed integrated path differential absorption lidar development for atmospheric CO₂ concentration measurements”, 26th International Laser Radar Conference, Porto Heli, Greece, 2012.
- [24] U. Singh, J. Yu, M. Petros, T. Refaat and K. Reithmaier, “Development of a Pulsed 2-micron Integrated Path Differential Absorption Lidar for CO₂ Measurement”, Proc. of SPIE Vol. 8872, 887209, 2013.
- [25] capable.larc.nasa.gov
- [26] www.hampton.gov
- [27] G. Anderson, S. Clough, F. Kneizys, J. Chetwynd, and E. Shettle, “AFGL atmospheric constituent profiles (0-120km),” Air Force Geophysics Laboratory, AFGL-TR-86-0110, 954, 1986.
- [28] www.noaa.gov